RI 9429

REPORT OF INVESTIGATIONS/1992

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Library of Congress Cataloging in Publication Data:

Bartels, John R.
Bending fatigue tests 2 and 3 on 2-inch 6×25 fiber core wire rope / by J.R. Bartels, W.M. McKewan, and A.J. Miscoe.

p. cm. — (Report of investigations; 9429)

Includes bibliographical references.

1. Mine hoisting—Equipment and supplies—Testing. 2. Wire rope—Fatigue—Testing. I. McKewan, William M. II. Miscoe, Anthony J. III. Title. IV. Series: Report of investigations (United States. Bureau of Mines); 9429.

TN23.U43 [TN339] 622 s—dc20 [622'.6] 92-13941 CIP

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

deg	degree	lb	pound
ft	foot	lbf·ft	pound (force) foot
ft/min	foot per minute	lbf·ft/kip	pound (force) foot per kip
in	inch	pct	percent
in/min	inch per minute	pct in/in	percent inch per inch
kip/in^2	kip per square inch	psi	pound (force) per square inch

BENDING FATIGUE TESTS 2 AND 3 ON 2-INCH 6×25 FIBER CORE WIRE ROPE

By J. R. Bartels,[1] W. M. McKewan,[2] and A. J. Miscoe[3]

ABSTRACT

The U.S. Bureau of Mines has established a wire rope research laboratory to examine the factors that affect the life of wire rope. Two 2-in-diameter 6×25 fiber core (FC) ropes were degraded on a bending fatigue machine. These were the second and third ropes in a series of tests on this construction and size rope. Tensile and nondestructive tests were performed on samples of the rope to determine the relationship between rope deterioration and rope breaking strength. The tests indicated that once a wire rope nears the end of its service life, both deterioration and the consequent loss of rope strength begin to increase at an accelerated rate.

[1]Civil engineer.
[2]Metallurgist.
[3]Supervisory physical scientist.
Pittsburgh Research Center, U.S. Bureau of Mines, Pittsburgh, PA.

INTRODUCTION

The wire rope research laboratory is located at the U.S. Bureau of Mines Pittsburgh Research Center in Bruceton, PA. The laboratory was set up as part of the hoisting system development project, which has been a continuing effort by the Bureau for several years. The primary goal of this project is to improve both the safety and efficiency of hoisting systems. A major part of this effort involves the study of the degradation of wire rope during its service life. Personnel-carrying hoists are used for transporting miners in hundreds of mines; failure of the rope in a single high-capacity hoist could result in a catastrophic accident.

The objective of the project is to enhance the safety of hoisting systems by quantifying the degradation process. The research approach is to develop accurate data on the factors that reduce wire rope life, such as fatigue (both bending and axial), wear, and corrosion. This data could be used to improve the evaluation of current nondestructive testing equipment data for determination of rope condition. Thus, it can be seen that the safety and economic concerns are interrelated and the potential benefits of such research are high.

EQUIPMENT DESCRIPTION

BENDING FATIGUE MACHINE

Because one of the primary modes of wire rope degradation is fatigue from bending on sheaves and drums, the principal machine in the laboratory is one designed to cause fatigue damage in varying degrees in a long sample of wire rope. By using a long sample, the possible variation among short samples is avoided. The bending fatigue machine is shown in figure 1 and a schematic diagram of the rope path is shown in figure 2.

The "three-sheave" configuration not only shortens the load frame, but also multiplies the number of rope-bending cycles for each machine cycle. Thus, in a single specimen, samples of rope at each of nine different levels of degradation will be obtained. The cycle profiles for these tests are shown in figure 3.

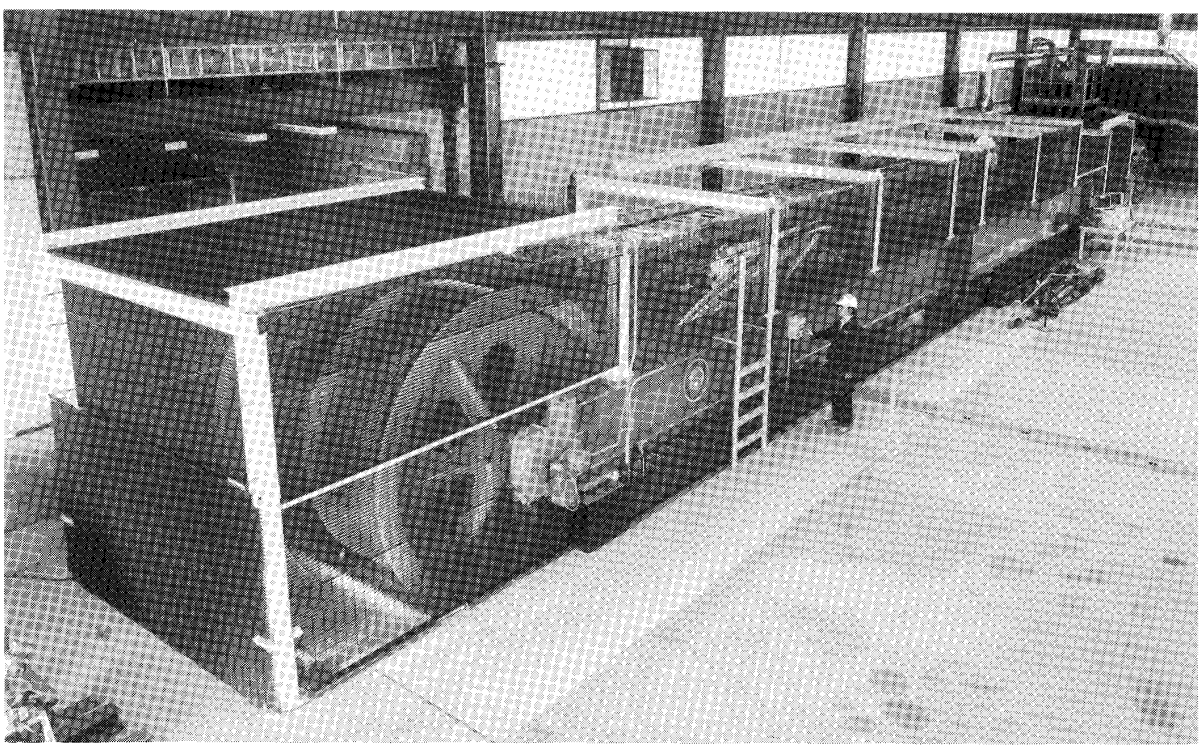

Figure 1.—Bending fatigue machine.

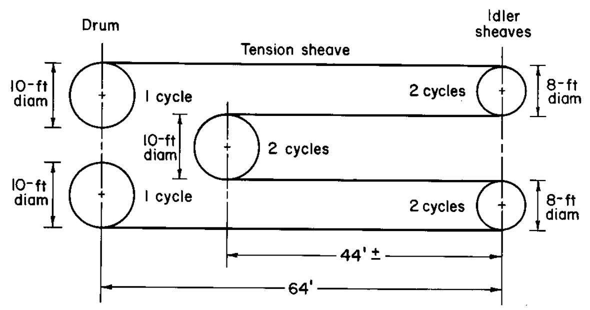

Figure 2.—Diagram of rope path.

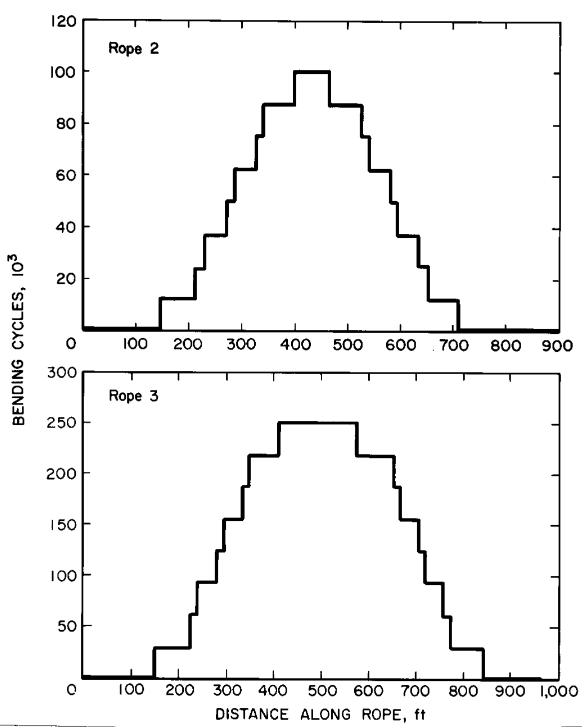

Figure 3.—Fatigue cycle profile.

Overall control of the machine is provided by a computer. The computer manages the hydraulic system as well as the drive system. The hydraulic system, through a ram on the center sheave, maintains constant rope tension and compensates for stretch in the rope. The computer also manages the braking system used for emergency shutdown when the computer detects an abnormal operating condition. Drum rotation is changed by an electrical regenerative braking system in the drive; thus, the hydraulically controlled friction brakes are a backup system. The computer is programmed to recognize and react to emergency situations (via a variety of sensors), such as when the tension cylinder runs out of travel, when the rope nears the end of the drum, or if the rope breaks. Operations are monitored continuously throughout a test. The bending fatigue machine is described in more detail in a previous publication.[4]

The current drum liner is flat, but can be replaced with other surface materials, such as urethane-coated materials or grooved liners, for future studies. The sheaves are made with bolt-on segments, which are replaceable for different rope diameters.

The specifications for the fatigue machine are given in table 1.

Table 1.—Specifications for bending fatigue machine

Maximum rope tension . . . . . . lb . .	300,000
Maximum rope speed . . . ft/min . .	1,000
Maximum fleet angle . . . . . . deg . .	2.9
Maximum rope stretch (without regripping) . . . . ft . .	20
Rope diam . . . . in . .	1-2½
Rope length . . . . ft . .	up to 1,100
Drum diam . . . . ft . .	10
Drum width . . . . ft . .	8.4
Tension sheave diam . . . . ft . .	10
Idler sheave diam . . . . ft . .	8

NONDESTRUCTIVE TESTING EQUIPMENT

During the test, two commercially available electromagnetic nondestructive testers (EM NDT's) were used. One was the Magnograph model MAG-1,[5] which is shown in figure 4. The other was the NDT Technologies model LMA-250, which is shown in figure 5.

Such devices are useful because they can examine the condition of the interior of a wire rope. However, their use is not mandatory under the wire rope retirement regulations of the U.S. Mine Safety and Health Administration (MSHA). They operate on the principle of magnetically saturating the test rope and then measuring any changes in the flux level from that of the new rope. As a rope wears, metal is lost and shows a lower level of flux leakage. Thus, these sensors measure the loss of metallic area (LMA). Because broken wires create magnetic anomalies, breaks are recorded as spikes on the chart and can be counted until the rope becomes deteriorated to the point where individual spikes cannot be distinguished. These breaks are known as local faults and are an indication of fatigue in the rope.

[4]McKewan, W. M., and A. J. Miscoe. Baseline Tensile Testing at the Wire Rope Research Laboratory. BuMines IC 9255, 1990, 23 pp.

[5]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

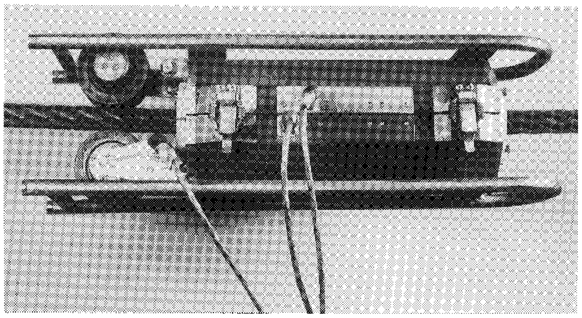

Figure 4.—Magnograph nondestructive sensor.

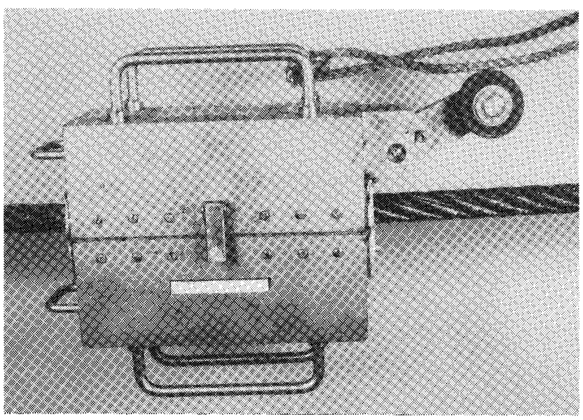

Figure 5.—NDT Technologies nondestructive sensor.

TENSILE AND AXIAL FATIGUE TESTING MACHINE

The second major piece of equipment in the laboratory is the tensile and axial fatigue testing machine shown in figure 6.

The tensile and axial fatigue testing machine was used to measure the actual breaking strengths of the new rope and the degraded rope samples from the bending fatigue test. The performance of this machine was reported in a previous publication.[6]

This hydraulically actuated machine is in a horizontal position rather than the usual vertical position to reduce vertical height requirements and for ease of access. The load is applied through a closed-loop servohydraulic system. The controllable parameters are displacement of the actuator, load applied to the specimen, and torque generated by the specimen as the axial load is applied. The system specifications are listed in table 2.

[6]McKewan, W. M., A. J. Miscoe, and J. R. Bartels. Bending Fatigue Test 1 on a 2-in 6×25 Fiber Core Wire Rope. BuMines RI 9408, 1992, 11 pp.

Table 2.—Capabilities of tensile and axial fatigue testing machine

Rope tension . . . . lb . .	800,000
Actuator speed . . . . in/min . .	32
Torque . . . . lbf·ft . .	20,800
Rope diam . . . . in . .	1-2½
Sample length . . . . ft . .	2-33

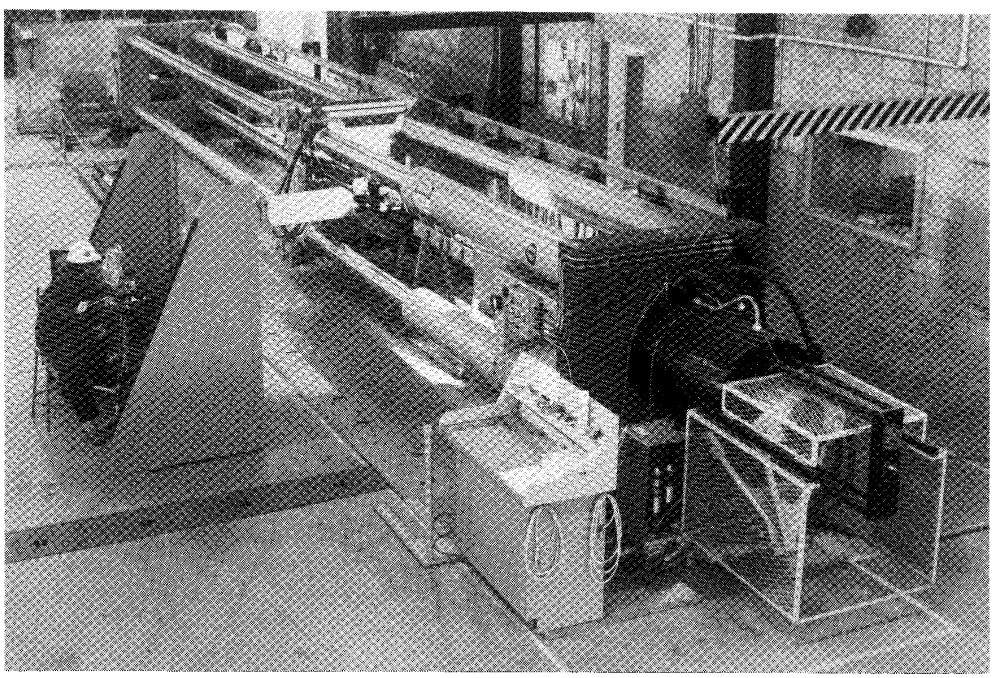

Figure 6.—Tensile and axial fatigue testing machine.

TEST ROPE DESCRIPTION

The test ropes were of 2-in-diameter 6×25 filler wire (FW) construction, improved plow steel, with a right regular lay of 13.13 in and an FC. In this construction (fig. 7), there are 6 strands containing 19 wires and 6 FW's for spacing; the FW's are not considered to be load bearing. The core is composed of polypropylene fiber. Thus, each rope is composed of 114 load-bearing wires. The measured breaking strength for these ropes when they were new was 348.8 kips. A rope after degradation is shown in figure 8.

TEST PROCEDURES

BENDING FATIGUE TEST

For the bending fatigue test, the rope specimens were reeved through the machine and wound onto the drum. The first rope in this controlled test was run at a conservative tension of 30 pct of breaking strength (100,000 lb) at a speed of 500 ft/min for a total of 12,512 machine cycles (which is equivalent to a maximum of 100,168 rope cycles) until the specimen appeared to be nearing failure. The second rope was run at 50 pct of breaking strength (170,000 lb) at a speed of 550 ft/min until the specimen broke on the machine at 3,157 machine cycles (which is equivalent to a maximum of 25,256 rope cycles). The test parameters are summarized in table 3.

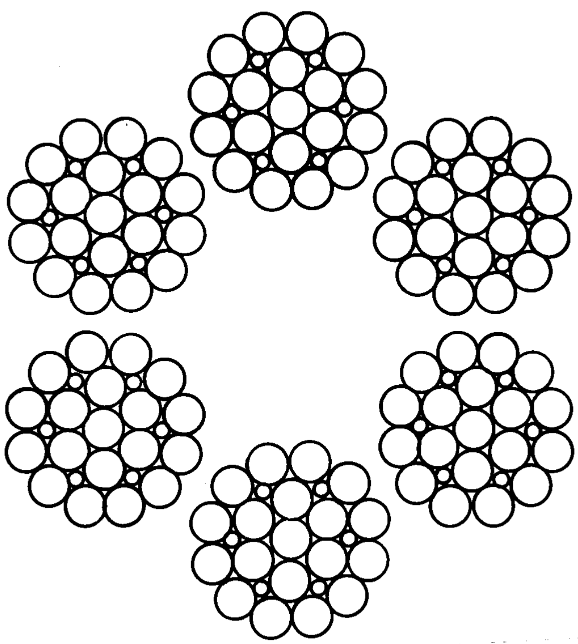

Figure 7.—Rope construction.

Table 3.—Specifications for bending fatigue tests

	Test 2	Test 3
Rope diam .... in . .	2	2
Rope length .... ft . .	878	988
Maximum fleet angle . . deg . .	2.30	100.000
Rope tension .... lb . .	100,000	170,000
Rope speed .... ft/min . .	500	550

When the ropes were removed, they were cut into 25-ft pieces. The selection of samples for further testing was based on the number of bending cycles. These samples were cut into three sections. Seventeen-foot-long pieces were used for tensile destructive tests. The remaining 5-ft pieces for wire-by-wire examination and 3-ft pieces for metallographical analysis were stored for later testing.

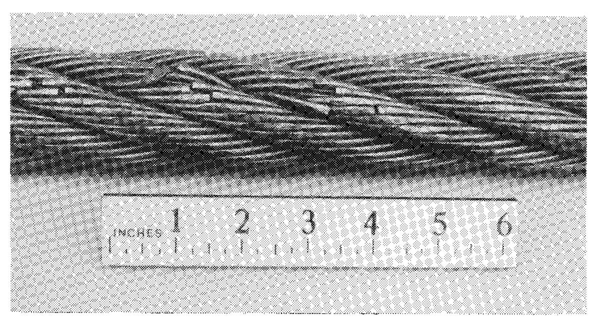

Figure 8.—Test rope after degradation.

TENSILE TESTING

The locations of the samples for the tensile tests are given in table 4. These samples were terminated with resin-filled, standard closed sockets, resulting in a finished specimen gauge length of about 15 ft. This length was chosen based on the results of a baseline testing program previously reported,[7] which determined that shorter samples would show abnormally high breaking strengths.

NONDESTRUCTIVE TESTING

For these tests, extra pieces of crown (outer) wire were imbedded between the strands, in coded order, at 50-ft intervals, to act as permanent markers on the EM NDT chart traces. To make a test, the rope is run through the instrument once to properly magnetize it. The sensor head is removed during rewinding to prevent a change in the magnetic polarity of the rope, and then the sensor head is remounted. The rope is then run through the instrument while the data are being recorded. The Magnograph nondestructive sensor was mounted on the rope where it leaves the top of the drum. The NDT Technologies nondestructive sensor was mounted on the rope where it winds onto the bottom of the drum. In these locations, 250 ft of rope that runs through the sheaves cannot be tested by both machines. However, with the sensors operating in opposite directions, the maximum length of rope is covered and the two chart traces overlap for comparison. A separate run was made for each instrument since the polarity of the magnetic fields is opposite with this arrangement. EM NDT tests were run weekly until a significant number of broken wires began to appear; then the tests were run more frequently. Sections of the chart records for these tests are shown in figure 9.

[7]Work cited in footnote 4.

Table 4.—Location of tensile test samples, feet

Test 2		Test 3	
Number of cycles	Location, ft	Number of cycles	Location, ft
0	38- 55, 813-830	0	38- 55, 943-960
12,521	163-180, 688-705	3,157	163-180, 793-810
37,563	238-255, 613-630	9,471	238-255, 743-760
62,320	288-305, 563-580	15,785	288-305, 668-685
87,647	338-355, 513-530	22,099	338-355, 618-635
87,647	363-380, 488-505	22,099	363-380, 593-610
100,168	413-430, 438-455	25,256	463-480, 513-530
		25,256	488-505

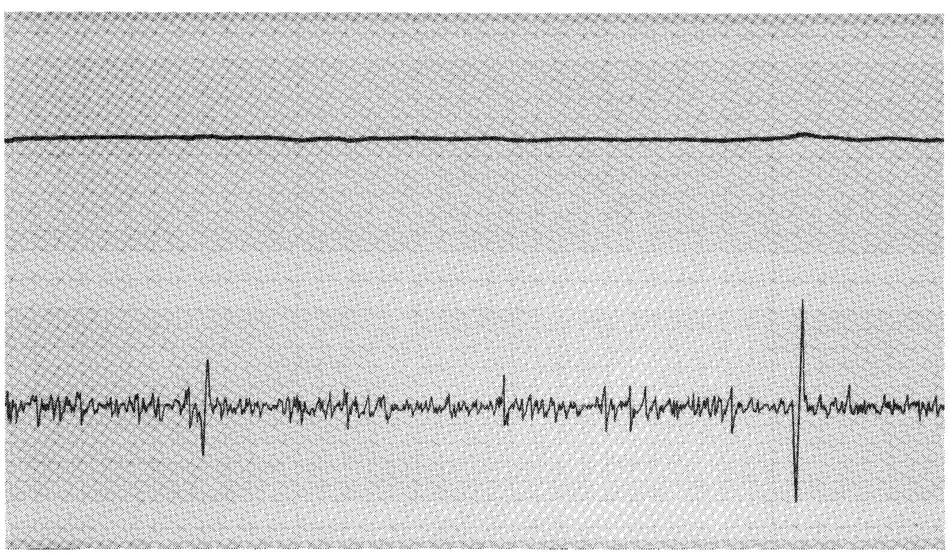

Figure 9.—Typical data from EM NDT.

RESULTS

The selected samples were socketed with approximately 15 ft between socket ends. The samples were then tested to failure on the tensile machine. The data obtained from tensile tests on the rope samples are shown in tables 5 and 6. The position in feet in the first column is the beginning of the sample.

Table 5.—Measured tensile test data

Position, ft	Number of bending cycles	Breaking load, kips	Elongation, in	Load loss, pct
		TEST 2		
38 ...	0	344.0	6.91	1.38
163 ..	12,521	340.4	5.42	2.41
238 ..	37,563	333.2	4.76	4.47
288 ..	62,605	322.9	4.74	7.43
338 ..	87,647	287.6	3.69	17.55
363 ..	87,647	283.5	3.82	18.72
413 ..	100,168	254.7	3.10	26.98
438 ..	100,168	254.2	3.13	27.12
488 ..	87,647	272.5	3.60	21.88
513 ..	87,647	293.4	4.06	15.88
563 ..	62,605	304.0	4.05	12.84
613 ..	37,563	320.1	4.65	8.23
688 ..	12,521	343.9	6.21	1.40
813 ..	0	343.8	7.53	1.43
(1) ...	0	348.8	8.67	0
		TEST 3		
38 ...	0	348.1	8.53	0.02
163 ..	3,157	342.6	5.54	1.78
238 ..	9,471	341.6	4.66	2.06
288 ..	15,785	342.5	4.66	1.81
338 ..	22,099	340.7	4.56	2.32
363 ..	22,099	333.7	4.09	4.33
463 ..	25,256	268.1	2.65	23.14
488 ..	25,256	217.0	2.85	37.79
513 ..	25,256	275.1	3.07	21.13
593 ..	22,099	313.1	3.34	10.24
618 ..	22,099	340.7	4.41	2.32
668 ..	15,785	337.2	4.36	3.33
743 ..	9,471	340.9	4.76	2.26
793 ..	3,157	346.7	5.94	.60
943 ..	0	348.2	8.27	.17
(1) ...	0	348.8	8.67	0

[1]New condition, sample taken from shipping reel.

The configuration of the bending fatigue machine allows a range of degradation to be achieved from a single test run. The data obtained from this test are indicative of wire rope degradation ranging from minimal wear to a condition of imminent rope failure. The controlled laboratory conditions allowed the testing of a sample with a 30 pct loss of strength, well beyond the MSHA retirement criteria of 10 pct strength loss.

Figure 10 shows the breaking load of the samples tested versus their respective position along the length of the rope. The center section of the rope had the most degradation and thus the maximum strength loss. Because the rope broke on the machine, the most deteriorated section in the center of rope 3 was not available for tensile testing. Because of the machine configuration, the strength loss in the first half of the rope is approximately a mirror image of the second half.

Figure 11 shows the effect of the number of bending cycles on breaking strength. As can be seen, the rope experienced a decrease in strength with a larger number of bending cycles. There is some scatter in the data, indicating that in these tests, the machine did not degrade the rope in exact symmetry. This duplication of results is still useful in evaluating the data.

There are two major factors relating to loss of strength considered for this test. One is LMA due to wear and the other is broken wires resulting from fatigue damage. Figure 12 shows the effect of the number of bending cycles on LMA, as determined by nondestructive methods. As can be seen, initially there is a rapid LMA as the top of the crown wires are worn, then the rate of LMA decreases as a larger bearing area is created by the wear, and finally the rate of LMA increases again as the adjacent wires start to wear. Other factors that affect strength loss, such as corrosion, will be investigated separately in future tests.

Figure 13 shows the effect of the number of bending cycles on the number of broken wires per lay length as determined visually. Initially there is a very gradual increase in the number of broken wires. However, as the

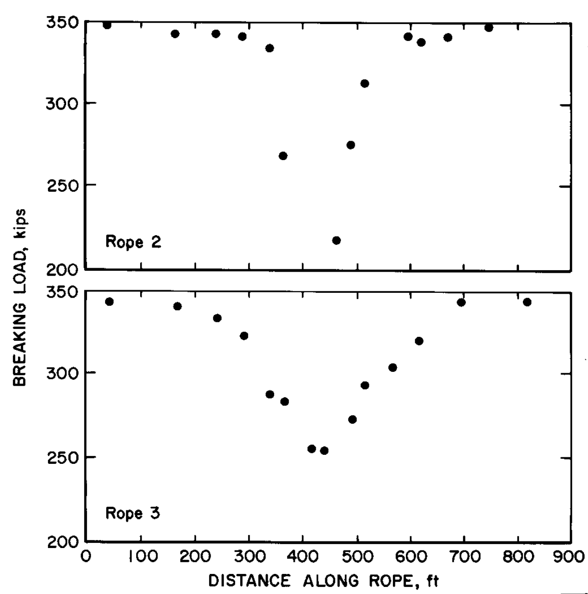

Figure 10.—Breaking load versus distance.

Table 6.—Calculated tensile test data

Position, ft	Number of bending cycles	Breaking		Yield		Modulus of elasticity, 10^6 psi	Torque K, lbf-ft/kip
		Stress, kip/in^2	Strain, pct in/in	Stress, kip/in^2	Strain, pct in/in		
ROPE 2							
38	0	213.0	3.68	164.8	1.68	11.24	14.4
163	12,521	210.8	2.89	168.9	1.74	13.41	13.0
238	37,563	206.4	2.54	169.6	1.40	14.08	13.6
288	62,605	199.9	2.52	166.1	1.45	13.33	13.5
336	87,674	178.1	1.96	158.2	1.45	13.07	13.7
363	87,674	175.6	2.04	152.4	1.38	13.21	13.8
413	100,168	157.7	1.66	145.2	1.33	13.00	14.1
438	100,168	157.4	1.67	146.0	1.34	12.92	14.3
488	87,674	168.8	1.91	151.7	1.38	12.82	14.2
513	87,674	181.7	2.16	155.8	1.41	13.41	14.0
563	62,605	188.2	2.16	159.6	1.41	13.63	14.1
613	37,563	198.2	2.47	164.6	1.50	14.02	14.1
688	12,512	212.9	3.30	165.9	1.45	13.58	14.3
813	0	212.9	4.00	160.7	1.61	11.63	14.5
ROPE 3							
38	0	215.6	4.54	164.0	1.67	11.25	14.6
163	3,157	212.2	2.94	178.8	1.51	13.75	13.8
238	9,471	211.6	2.47	184.6	1.49	14.52	13.2
288	15,785	212.1	2.48	184.1	1.48	14.87	13.2
338	22,099	209.7	2.43	182.2	1.45	15.16	13.3
363	22,099	206.6	2.17	184.6	1.46	13.21	13.3
413	25,256	166.0	1.41	166.6	1.43	14.31	13.6
438	25,256	161.3	1.51	165.7	1.60	12.19	11.6
488	25,256	170.1	1.63	165.1	1.45	13.58	13.6
513	22,099	193.9	1.78	181.3	1.46	15.04	13.3
593	22,099	211.0	2.35	189.7	1.51	15.06	13.3
618	15,785	208.8	2.31	183.7	1.50	14.52	13.5
668	9,471	211.1	2.53	181.6	1.48	145.50	13.6
743	3,157	214.7	3.14	176.9	1.48	13.89	14.0
943	0	215.6	4.40	163.3	1.70	11.18	14.7

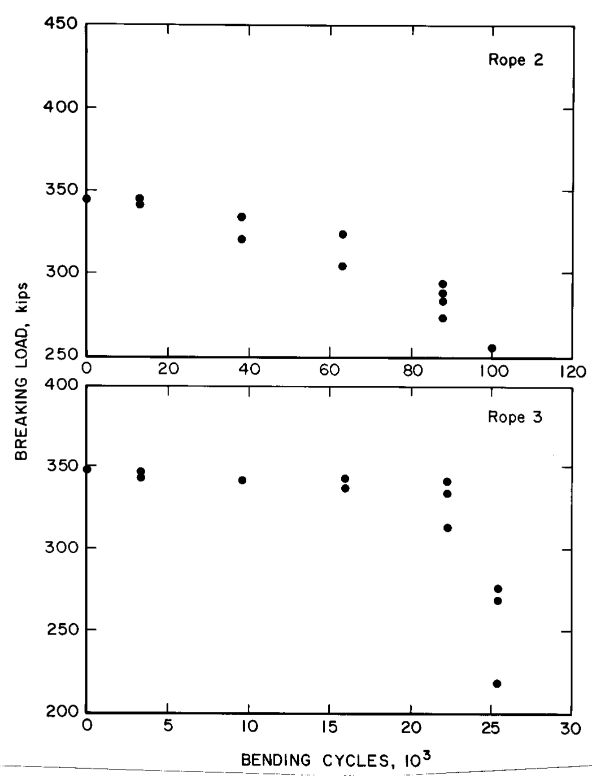

Figure 11.—Breaking load versus bending cycles.

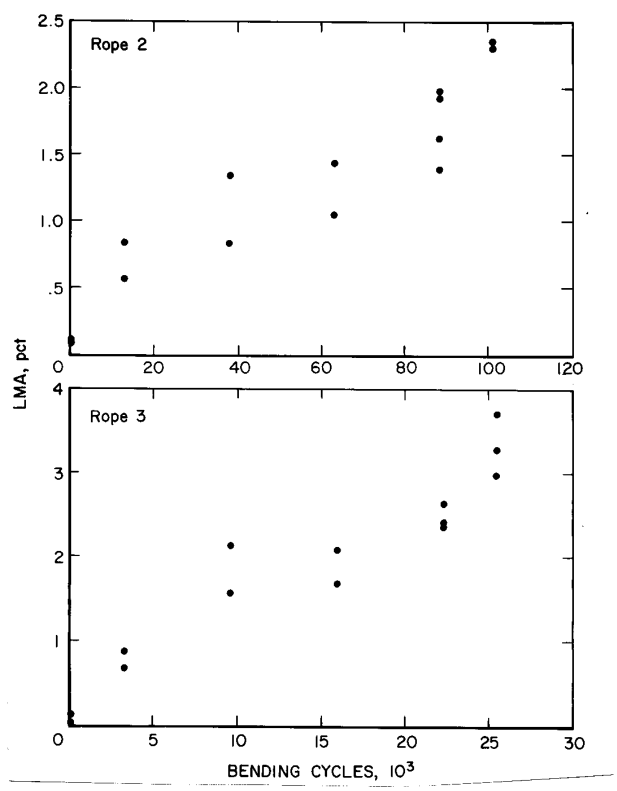

Figure 12.—LMA versus bending cycles.

rope becomes more fatigued, the rate at which wires break dramatically increases. Cold working could not be quantitatively measured; however, breaking strain is a good indicator. The decreased breaking strain indicates that cold working reduces the ductility of the wires. The effect of bending cycles on breaking elongation is shown in figure 14.

Table 7 contains data from other physical measurements that were made. The first two columns list the linear location and number of cycles at that location. The third column shows the rope diameter, as measured by a caliper, averaged from three positions around the rope. The fourth and fifth columns are computations of the percentage reduction in diameter and metallic area as compared with the best pieces. The LMA is obtained from an inhouse computer program that will be reported in the near future. The LMA computed from caliper readings (column 5) is compared to the LMA determined by the average reading from the two EM NDT sensors (column 6) in figure 15.

Figure 15 shows that the two areas are fairly close (within approximately 2 pct of the total LMA) over the length of the rope. This indicates that the two methods are comparable to each other even though neither is a panacea. EM NDT devices measure metallic mass, which can be affected by such things as rope tension, but will not detect such things as inner wire peenning. The caliper readings measure outside rope diameter, which can be used to calculate outer wire wear, but cannot detect such things as corrosion or nonwear causes of diameter loss such as milking, a condition resulting from the progressive movement of strands along the axis of the rope. Despite these shortcomings, both methods do provide an acceptable means of determining rope condition.

Table 7.—Diameter and EM NDT measurements

Position, ft	Number of bending cycles	Rope diam, in	Rope diam, Loss, pct	Area loss, pct, Calc	Area loss, pct, EM NDT	Wire diam loss, pct
			TEST 2			
38 ...	0	2.057	0.68	0.10	0.0	0.54
163 ..	12,521	2.013	2.80	.38	.0	22.5
238 ..	37,563	2.00	1.34	1.34	.0	27.6
288 ..	62,605	1.998	3.52	1.43	.0	28.3
338 ..	87,647	1.987	4.06	1.97	.3	32.6
363 ..	87,647	1.988	4.01	1.92	1.0	32.2
413 ..	100,168	1.980	4.39	2.34	1.0	35.3
438 ..	100,168	1.981	4.35	2.29	1.0	34.9
488 ..	87,647	1.999	3.48	1.39	2.0	27.9
513 ..	87,647	1.994	3.72	1.62	2.5	29.9
563 ..	62,605	2.007	3.09	1.05	2.1	24.8
613 ..	37,563	2.013	2.80	.83	2.0	22.5
688 ..	12,521	2.025	2.22	.56	1.0	17.9
813 ..	0	2.055	.77	.12	1.0	6.2
(1) ...	0	2.070	.0	.0	.0	.0
			TEST 3			
38 ...	0	2.056	0.72	0.11	0.0	5.8
163 ..	3,157	2.012	.87	.87	.5	22.9
238 ..	9,471	1.984	4.20	2.13	.5	33.8
288 ..	15,785	1.985	4.15	2.08	.5	33.4
338 ..	22,099	1.979	4.44	2.40	1.0	35.7
363 ..	22,099	1.980	4.39	2.34	1.0	35.3
463 ..	25,256	1.957	5.50	3.70	2.0	44.3
488 ..	25,256	1.969	4.92	2.97	2.0	39.6
513 ..	25,256	1.964	5.17	3.27	2.0	41.5
593 ..	22,099	1.975	4.64	2.26	1.5	37.3
618 ..	22,099	1.980	4.39	2.34	1.5	35.3
668 ..	15,785	1.993	3.77	1.67	1.0	30.3
743 ..	9,471	1.995	3.67	1.57	1.0	29.5
793 ..	3,157	2.019	2.51	.67	.5	20.2
943 ..	0	2.066	.24	.0	.0	1.9
(1) ...	0	2.070	.0	.0	.0	.0

[1]New condition, sample taken from shipping reel.

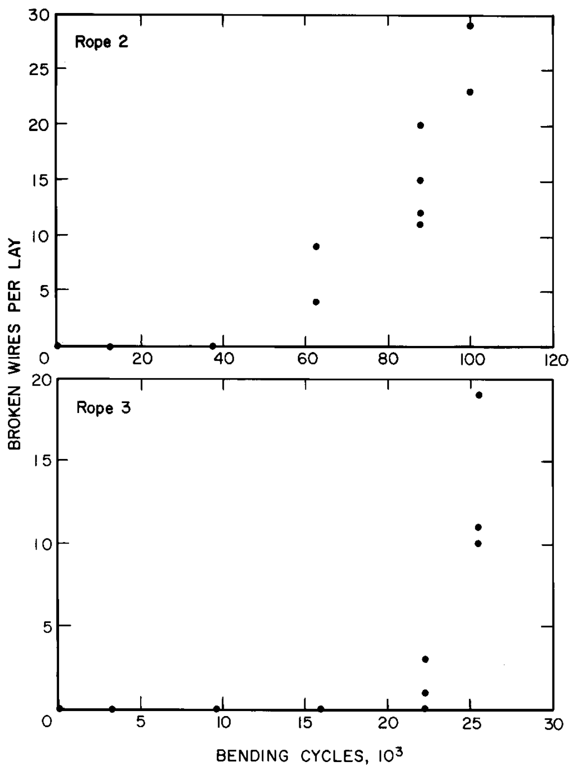

Figure 13.—Broken wires versus bending cycles.

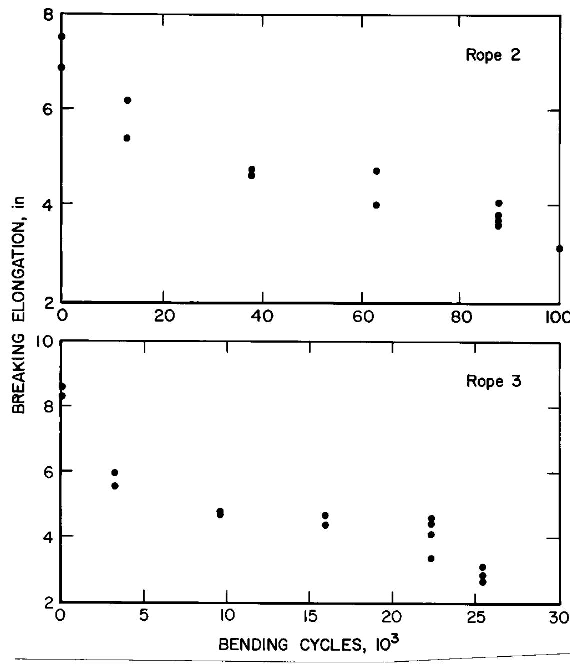

Figure 14.—Breaking elongation versus bending cycles.

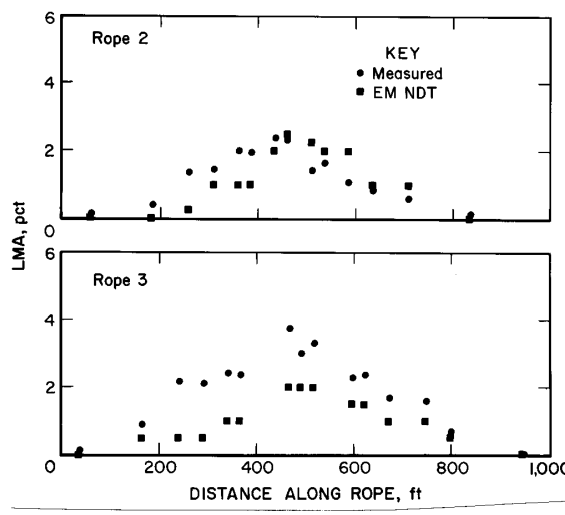

Figure 15.—Calculated and measured LMA versus distance.

The final column of table 7 shows the percentage loss of diameter of the outer wires of the rope, which also was determined by the previously mentioned computer program.

Table 8 shows the tabulation of a visual count of the number of broken wires per lay on the surface of the rope. These are the averages for two lay lengths.

Figure 16 shows how the breaking strength decreases with an increase in the number of broken wires.

Table 6 shows the data computed from the measurements made during the tensile tests.

Breaking stress and strain are computed by the operating program when the rope specifications are inserted. The beginning of the plastic deformation is determined by inspection, and then yield stress and strain are computed using the 0.2 pct offset as is customary for testing steel samples.

The effect of the number of cycles on the modulus of elasticity is shown in figure 17. The modulus of elasticity increases with distance and then decreases as wires begin to break. Again, the approximate symmetry between the left and right halves of the rope can be seen.

Torque K is the slope of the curve in a plot of load versus the torque generated by a rope sample during a tensile test. The slope is a straight line until just before rupture. Table 6 shows that torque K is relatively insensitive to increased cycling, probably because of the helical configuration of the wires in the rope structure.

Table 8.—Broken wires data

Rope 2			Rope 3		
Position, ft	Number of bending cycles	Number of broken wires	Position, ft	Number of bending cycles	Number of broken wires
38	0	0	38	0	0
163	12,521	0	163	3,157	0
238	37,563	0	238	9,471	0
288	62,605	9	288	15,785	0
338	87,674	15	338	22,099	0
363	87,674	20	363	22,099	1
413	100,168	29	463	25,256	11
438	100,168	23	488	25,256	19
488	87,674	11	513	25,256	10
513	87,674	12	593	22,099	3
563	62,605	4	618	22,099	1
613	37,563	0	668	15,785	0
688	12,512	0	743	9,471	0
813	0	0	793	3,157	0
			943	0	0

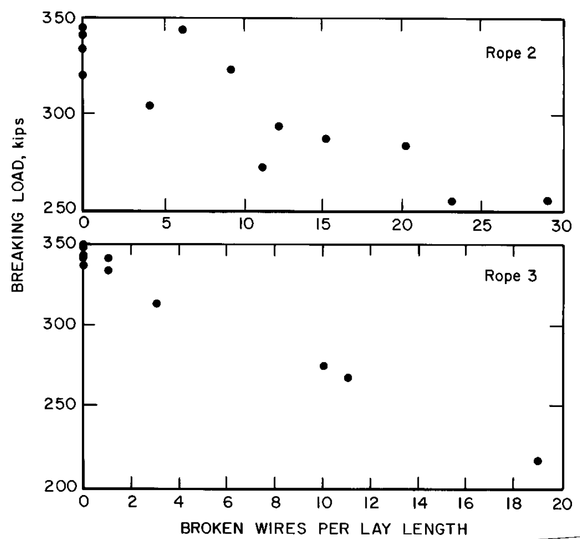

Figure 16.—Breaking load versus broken wires.

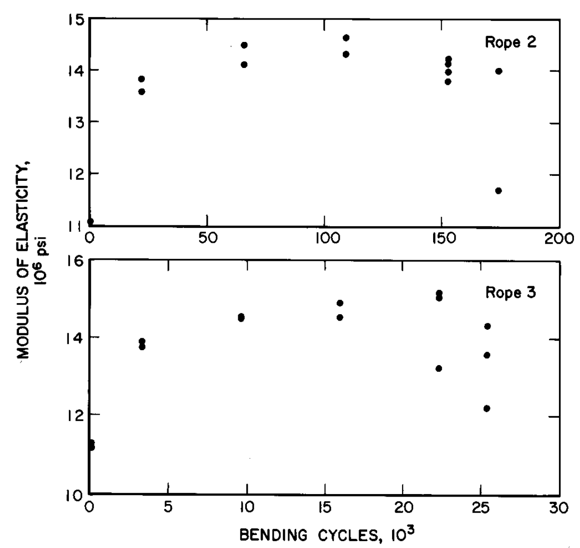

Figure 17.—Modulus of elasticity versus bending cycles.

CONCLUSIONS

The second and third ropes in a series of tests on 2-in 6×25 FC wire ropes have indicated several important factors that will be significant in future testing at the Bureau's wire rope laboratory. First, higher than normal rope loads tend to produce rope degradation primarily in the form of fatigue and broken wires with minimal LMA. This characteristic will be useful in isolating the various components of rope degradation so that they may be studied separately. Second, the fact that measured and calculated LMA's are within approximately 2 pct of total LMA indicates that electromagnetic testing and diameter measurements are comparable methods of measuring LMA in in situ field applications. Finally, even though fatigue damage was not directly measurable, the breaking strain, the modulus of elasticity, and the broken wires provide confirmation of its presence.

As the number of rope bending cycles increases, the rope tends to reach a point where the combination of LMA and number of broken wires increases at an accelerated rate. This accelerated rate of deterioration results in a rapid decrease in the breaking strength of the rope. Further testing and analysis will be necessary to determine the significance of this deterioration to field installations.